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(Article begins on next page)

1 FIELD MEASUREMENTS BASED MODEL FOR SURFACE 2 IRRIGATION EFFICIENCY ASSESSMENT

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8 **Abstract**

9 Within scenarios of water scarcity, the irrigation efficiency plays an increasingly strategic role. In
10 this paper, a method that uses an advance-infiltration model based on four field measurements and
11 the soil particle size distribution is proposed to estimate border-irrigation efficiencies. This method
12 was applied to fifteen irrigation events and the application, storage and distribution efficiencies
13 were estimated. The advance-infiltration model was validated against soil moisture measurements.
14 The field-scale saturated hydraulic conductivity was estimated by model fitting to the measured
15 depth of water infiltration. The sensitivity of the modelled irrigation efficiency to the operational
16 surface irrigation parameters was evaluated by simulating seven irrigation scenarios based on field-
17 collected data.

18 The infiltration profiles obtained by the proposed method were in agreement with the soil moisture
19 measurements. The maximum difference between simulated and measured infiltration depth was
20 0.018 m . The field-scale saturated hydraulic conductivity values were in agreement with the
21 infiltrometer tests results. The analysis of both simulated scenarios and monitored irrigation events
22 highlighted the need for farmers to reduce the flow rates and increase the duration of irrigation
23 events, in order to improve the irrigation efficiencies.

24 **Keywords:** agricultural hydrology; surface irrigation; irrigation efficiency; irrigation modelling.

25 **1 Introduction**

26 Because of the ever-increasing demand for water, analyses of irrigation efficiency have assumed an
27 important role in Italy and throughout the entire Mediterranean area (Chohin-Kuper et al., 2003;
28 Fereres and Soriano, 2007; Inglesias et al., 2007). Additionally, climate change is expected to
29 increase water scarcity (Arnell, 1999; Inglesias et al., 2007).

30 On the western Po River Plain (Piedmont, northern Italy), where corn (*Zea mays* L.) is the most
31 widely grown crop, surface irrigation systems are primarily used. Thus, for water resource
32 management programmes (for which it is necessary to evaluate and reach a compromise between
33 the constraints imposed by water scarcity and the production requirements) the analysis of the
34 irrigation efficiencies of surface irrigation systems has become an essential tool.

35 To calculate the dependence of irrigation efficiency on irrigation parameters, three different
36 strategies may be adopted: i) a detailed simulation of infiltration (e.g., Manzini and Ferraris, 2004;
37 Ferraris et al., 2012); ii) a detailed simulation of infiltration coupled with the surface advance of
38 water (e.g., Gandolfi and Savi, 2000); and iii) an analytical solution to the Lewis and Milne (1938)
39 integral equation (Philip and Farrell, 1964).

40 Because the latter strategy requires a low number of parameters, it is suitable for providing a field-
41 scale description of the rates of water advance and infiltration for practical uses (such as managing
42 irrigation performance). In particular, when related to an infiltration function such as that of Philip
43 (1957), which considers the saturated hydraulic conductivity, the Philip and Farrell analytical
44 solution solves the advance-infiltration problem.

45 Although the Philip and Farrell analytical solution is only valid for short irrigation durations and
46 cannot accurately predict long-term behaviour (Knight, 1980), this solution has been employed by
47 several authors to successfully describe the advance-infiltration problem for surface irrigation
48 management (e.g., Collis-George and Freebairn, 1979; Or and Silva, 1996).

49 The Philip (1957) infiltration function, used in the Philip and Farrell (1964) analytical solution,
50 requires knowledge of soil hydraulic parameters to estimate the soil infiltration dynamics. Several
51 authors have indicated that the Beerkan Estimation of Soil pedoTransfer (BEST) infiltration test

proposed by Lassabatère et al. (2006) is an effective method for the hydraulic characterisation of soils directly in the field (e.g., Mubarak et al., 2009; Xu et al., 2009; Bagarello et al., 2011). Bagarello et al. (2011) investigated the possibility of simplifying the particle size distribution curve (PSD) fitting by including only three points (the clay, silt and sand contents) instead of fourteen points. These authors found the simplified PSD to be a reliable alternative to the normal procedure. Other methods have been recently developed for irrigation and management purposes (e.g.: Bautista et al., 2009; Strelkoff et al., 2009), which use surface water depth and mass balance methods to estimate the infiltration. Also, an interesting new analytical solution has been developed (Cook et al., 2013). However, it is beyond the scope of this paper to compare different analytical solutions. The proposed method is based on the direct measurement of the infiltration depth to calibrate the infiltration advance model, and to estimate the saturated hydraulic conductivity at the field scale. Within the context of this the above mentioned simplification, this study aims to propose a method for the calculation of border-irrigation efficiencies by using an advance-infiltration model and four simple field measurements: i) the inflow rate; ii) the irrigation duration; iii) the water head imposed on the field surface during an irrigation event and iv) the monitoring of the soil water content at only one point in the field at only the beginning and the end of the irrigation process. The second objective of this study was to use the proposed method to evaluate the surface irrigation efficiency of irrigation events based on the actual practices adopted by farmers. Hence, this method can provide a simulation tool that is able to analyse the effects of differences in management practices on irrigation efficiency.

2 Methodology

2.1 Advance-infiltration models

Irrigation efficiencies depend on the volume of water infiltrated during the irrigation event and on the distribution of the infiltrated water across the field. To compute the infiltrated volume of water and assess its distribution, it is necessary to determine the infiltration profile across the field. This

infiltration profile can be obtained from the solution of the infiltration advance across the field. The infiltration advance is calculated from the simultaneous solution of two equations: the analytical solution to the Lewis-Milne (1938) differential equation proposed by Philip and Farrell (1964) to describe the advance of the water front and the infiltration equation of Philip (1957). These two equations are written as:

$$\frac{x}{q} = \frac{1}{C} \left[1 - \exp\left(\frac{4C^2 t}{\pi \cdot S^2}\right) \operatorname{erfc} \frac{2Ct^{1/2}}{\pi^{1/2} S} \right], \text{ and} \quad (1)$$

$$I = S\sqrt{t} + Ct, \quad (2)$$

where, x (L) is the horizontal spatial coordinate of the water advance front; q ($L^2 T^{-1}$) is the inflow rate per unit of width; C ($L T^{-1}$) is a parameter related to the saturated hydraulic conductivity K_s ($L T^{-1}$) according to the relation proposed by Haverkamp et al. (1988):

$$\frac{1}{3} K_s \leq C \leq \frac{2}{3} K_s, \quad (3)$$

which depends on the initial soil water content; t (T) is the time; S ($L T^{-1/2}$) is the sorptivity; I (L) is the cumulative infiltration at any chosen value of x .

In this study, the parameter C was considered as constant and equal to $K_s/2$, as suggested by Parlange (1977). Such an assumption is valid because C is only slightly dependent on the initial water content (Philip 1957), and for most practical purposes, any change in C may be neglected. This assumption is not made because C does not change, but the changes in C are relevant for long-term infiltration rates, which are not considered in this work, and may be caused by changes in the saturated hydraulic conductivity (Samani and Yitayew 1989; Silva 1995) in association with changes in the near-surface soil porosity. Because long-term infiltration rates are not considered in this work, the Philip and Farrel analytical solution can be applied. In fact, the Philip and Farrell analytical solution should only be considered valid for short irrigation durations and should not be applied to accurately predict long-term behaviour (Knight, 1980). The method proposed by Knight

100 (1980) to verify short-duration conditions has been adopted in this work and is presented in the
 101 following section.

102 Sorptivity is defined as a function of the scale parameters of the water retention and hydraulic
 103 conductivity curves according to the relationship proposed by Parlange (1975):

$$104 \quad S^2 = \int_{\theta_i}^{\theta_s} (\theta_s + \theta - 2\theta_i) K \frac{dh}{d\theta} d\theta \quad (4)$$

105 where, θ_s ($L^3 L^{-3}$) is the soil water content at saturation; θ ($L^3 L^{-3}$) is the actual soil water content; θ_i
 106 ($L^3 L^{-3}$) is the initial soil water content; K ($L T^{-1}$) is the soil hydraulic conductivity at θ ; h (-L) is the
 107 actual matric potential.

108 In this study, the van Genuchten (1980) equation and the Brooks and Corey (1964) relationship
 109 were chosen as the models for calculating the water retention and hydraulic conductivity,
 110 respectively. The effect of hysteresis on the water retention curve was neglected, but it can be
 111 incorporated by including a hysteresis model, as suggested by Canone et al., 2008.

112 Hence, by integrating Eq. (4) within the water content range, one obtains:

$$113 \quad S^2 = (\theta_i, \theta_s) = -C_p \theta_s K_s h_g \left(1 - \frac{\theta_i}{\theta_s} \right) \left[1 - \left(\frac{\theta_i}{\theta_s} \right)^\eta \right] \quad (5)$$

114 Where, h_g (-L) is the matric potential scale parameter of the van Genuchten (1980) equation; K_s (L
 115 T^{-1}) and η (L) are the scale parameter and shape parameter of the Brooks and Corey (1964)
 116 equation; C_p (-) is a soil-dependent constant (Haverkamp et al., 2006) depending on the shape
 117 parameters m and n of the van Genuchten (1980) equation.

118 Equation (1) is a function of S , K_s and q , and equation (2) is function of S and K_s . Since the method
 119 was applied to estimate the irrigation efficiency of border irrigation, the flow rate was measured at
 120 the inlet of a bay located at the centre of the field. The flow rate (q) was assessed by measurement
 121 of the cross-sectional area and the measurement of the current velocity. The latter was determined
 122 with a propeller flow meter OTT C2 (OTT Hydromet, Kempton, Germany, UE), which was

123 installed before any irrigation monitoring and removed at the end of it. S and K_S are not directly
 124 measurable. In the proposed approach, the sorptivity is computed by solving equation (5), which
 125 requires the values of θ_s , θ_i , K_S , h_g , η , m and n .

126 The soil water content at saturation and the initial soil water content were measured at a time
 127 domain reflectometry (TDR) station located at one point in the field. The matric potential scale
 128 parameter (h_g) was calculated using the soil-independent conceptual model proposed by
 129 Vanclooster et al. (2011) to predict the soil water retention curve from the cumulative particle size
 130 distribution (PSD) curve and the void ratio.

131 In this study, the shape parameters m , n and η were determined from the PSD curve as suggested by
 132 Haverkamp et al., 2002. The PSD curve was fitted to five points obtained from the analysis of soil
 133 samples collected at an upstream, a centre and a downstream position along the bay under study.
 134 The particle size analysis was performed according to the pipette method, which is based on the
 135 difference in sedimentation speed between small and large soil particles. As demonstrated by
 136 Bagarello et al. (2011), the use of five points to fit a cumulative particle size distribution curve is
 137 sufficient for determining soil hydraulic parameters.

138 In the proposed approach, the saturated hydraulic conductivity ~~is~~ was the only parameter that cannot
 139 be measured. The field-equivalent value (K_{Seq}) ~~is~~ was determined by model fitting. Equations (1)
 140 and (2) were fitted to the depth of water infiltration at the end of an irrigation event. In Eqs. (1) and
 141 (2) C was considered equal to $0.5K_{Seq}$ and S was replaced by Eq. (5), so that only K_{Seq} was obtained
 142 by model fitting. The depth of water infiltration ~~is~~ was calculated from the water content data
 143 measured at the TDR station at the start and at the end of the irrigation event, following the
 144 methodology presented in section 2.5. The advance-infiltration model was validated against four
 145 depths of water infiltration at four times in-between the start and the end of the irrigation event.

146 The differences between the simulated (I_s) and measured (I_m) infiltration depth were compared to
 147 Cook et al. (2013) results employing the square root of the Nash-Sutcliffe efficiency coefficient
 148 (Nash and Sutcliffe, 1970), given by the following relation:

$$RSR = \frac{\sqrt{\sum_{i=1}^N (I_m(t_i) - I_s(t_i))^2}}{\sqrt{\sum_{i=1}^N (I_m(t_i) - \bar{I}_m)^2}}, \quad (6)$$

where N is the number of simulated and measured infiltration depths and t is time (s).

Following the procedure explained above, the field equivalent sorptivity and the saturated hydraulic conductivity were determined once per year at each surveyed farm. These estimated field-equivalent parameters were used to calculate the advance-infiltration profiles for each irrigation event performed by the farmers and monitored within the study period.

Each saturated hydraulic conductivity value estimated using the proposed approach was compared to three values of saturated hydraulic conductivity estimated by BEST tests performed at the same location where the soil samples were collected, as explained in section 2.3. For the sake of comparison, the K_S values were also determined by seven pedotransfer functions based on particle size distribution data and θ_s (namely, Brakensiek et al., 1984; Cosby et al., 1984; Puckett et al., 1985; Saxton et al., 1986; Campbell and Shiozawa, 1994; Dane and Puckett, 1994; Ferrer-Julà et al., 2004).

2.2 Verification of the assumption of short irrigation duration

According to the limitations of the advance-infiltration model proposed by Philip and Farrell (1964) for predicting long-term infiltration processes, the short irrigation duration assumption has to be verified to employ this advance-infiltration model. In the proposed approach, the verification of the assumption is performed according to the methodology proposed by Knight (1980), which requires three variables. The first is a dimensionless time variable defined as:

$$\tau_k = K_S^2 t / S^2. \quad (7)$$

The second is a dimensionless variable for the head on the soil surface given by:

$$C_k = K_S h_{surf} / S^2, \quad (8)$$

where, h_{surf} (L) is the water head imposed on the field surface during the irrigation process.

172 The third is a dimensionless advancement variable given by the “linear” soil function proposed by
 173 Philip (1966, 1969), which, at small times, is given by the following equation when $C \neq 0$:

$$174 \quad x_k = \frac{\tau}{C_k} - \frac{2\tau^{3/2}}{3C_k^2} - \frac{(2C_k - \pi)\tau^2}{8C_k} - \frac{(2C_k^2 - 4C_k\pi + \pi^2)\tau^{5/2}}{15\pi C_k^4}. \quad (9)$$

175 The dimensionless advancement is calculated by employing the linear soil function (Eq. 9)
 176 proposed by Philip (1966, 1969). Both the dimensionless advancement and time variables are
 177 compared to their maximum values ($\tau_{max} = 1.4$ and $x_{max} = 0.4$), which are the limits of the area of a
 178 τ - x_k plot for which the time can be considered short. Because the Philip and Farrell advance-
 179 infiltration model behaves as the linear soil function, proposed by Philip (1966, 1969), for any
 180 values of C_k within the range between 0 and 2 (Knight, 1980), the short duration assumption is
 181 verified for τ_k and x_k values lower than τ_{max} and x_{max} , respectively.

182 2.3 Saturated hydraulic conductivity validation

183 In this study, the BEST infiltration test (Lassabatère et al., 2006) was employed to obtain an
 184 estimation of K_S that is independent from the advance-infiltration model and the soil water content
 185 measured by the TDR station. These independent values of K_S were determined once a year at the
 186 same locations where the soil samples were collected. They were compared to the K_{Seq} values
 187 estimated following the methodology presented in section 2.1 to validate the latter.

188 In the BEST procedure, the scale parameter for the residual water content (θ_r) was assumed to be
 189 zero, and the initial soil water content and the soil water content at field saturation (θ_s) were
 190 estimated using the TDR measurements collected before and after the infiltration tests. The values
 191 of K_S and S were determined by fitting the experimental infiltration data to the set of equations
 192 proposed by Lassabatère et al. (2006). Finally, the scale parameter for the matric potential (h_g) for
 193 the water retention curve of van Genuchten (1980) was obtained using Eq. (5).

194 2.4 Farm descriptions

195 Three farms, characterized by their analogous soil conditions were selected as testing sites. All
 196 farms performed border irrigation on corn (*Zea mays* L.) crops. These farms are located in the

197 Cuneo district (namely: farm 1, Ceresole d'Alba, Lat. 44° 48' 37", Lon. 7° 46' 45"; farm 2,
 198 Fossano, Lat. 44° 34' 40", Lon. 7° 42' 06"; farm 3, Sommariva del Bosco, Lat. 44° 44' 21", Lon. 7°
 199 43' 33") in north-western Italy. The soil of the three farms, were analysed according to the USDA
 200 Keys to Soil Taxonomy (Soil Survey Staff, 2010), and belong to the following families: farm 1,
 201 Fluventic Dystrudept, coarse-loamy, mixed, nonacid, mesic; farm 2, Acquic Haplustept, coarse-
 202 loamy over loamy-skeletal, mixed, nonacid, mesic; farm 3, Acquic Haplustept, loamy-
 203 skeletal, mixed, nonacid, mesic.

204 Despite the fact that the soils belonged to similar textural classes (i.e., loam and silty loam), the
 205 soils exhibited differences in their hydraulic properties (e.g., the soil water content at saturation
 206 conditions and the field capacity, listed in Table 1) primarily because of the differences in tillage
 207 practices and the varying percentages of stones in the fields. The percentages of sand, clay, and silt
 208 (defined according to the USDA Classification System (Soil Survey Laboratory Staff, 1992)) are
 209 included in Table 2 and were calculated from the average of the laboratory analysis of four samples
 210 collected at four different depths (between 0.05 m and 0.6 m). The percentages of stones were
 211 determined from the analysis of two vertical soil profiles for each field. These analyses were
 212 performed during the 2007 irrigation season.

213 During the three-year period (2006-2008), the farmers executed thirty irrigation events, and fifteen
 214 were monitored with specific measurement campaigns. In such a period, the border sizes of these
 215 farms changed (Table 3) because the farmers autonomously followed their normal habits regarding
 216 cultivation management and irrigation practices. However, the practices of the farmers are crucial
 217 for the study because monitoring real-world agriculture was one of the study's main objectives. All
 218 farmers cultivated the corn (*Zea mays* L.) on bays composed by multiple rows (10 rows per bay at
 219 farm 1, 13 rows per bay at farm 2, and 8 rows per bay at farm 3) with interrow spacing of 0.75 m.
 220 The rows were oriented along the maximum field length. At the end of the field a small canal to
 221 collect surface runoff was seasonally dug.

222 2.5 TDR stations

223 Time Domain Reflectometry is a well-known technique that is commonly accepted for the
224 assessment of water content and other physical properties of porous media by permittivity
225 measurements (Topp et al., 1980; Robinson et al., 2003; Canone et al., 2009; Baudena et al., 2012;
226 Previati et al., 2012). Soil permittivity measurements were carried out using a device composed by
227 one TDR cable tester (Tektronix Metallic Cable Tester 1502C manufactured by Tektronix Inc.,
228 Beaverton, OR, USA) connected to a notebook and a multiplexer. The system allowed automatic
229 measurements of soil permittivity at eight points along the soil profile. The TDR signals were
230 sampled and acquired using the WinTDR software (Or et al., 2004) and stored in the hard disk of a
231 notebook. The soil bulk permittivity was monitored from the beginning to the end of the irrigation
232 events at a time interval of 3 minutes, and the volumetric soil water content was computed using the
233 composite dielectric approach described by Roth et al. (1990).

234 The installed TDR probes were 150 mm long and were composed of three stainless steel rods held
235 together by a nylon spacer. All of the probes were calibrated according to the method proposed by
236 Heimovaara (1993). All of the connections were made using RG58 50 Ω coaxial cables. Each of the
237 10 probes was horizontally inserted into the soil. The probes were arranged in two vertical profiles
238 at the depths of 0.05 m, 0.15 m, 0.30 m, 0.45 m, and 0.65 m to monitor the entire root zone. In one
239 of the fifteen examined cases, a layer of stones prevented the 0.65 m depth measurement (Fig. 1).
240 The TDR stations were located at approximately one-third of the field length along a bay situated at
241 the centre of the field.

242 Each volumetric water content measurement was then associated with and weighted in relation to its
243 specific corresponding volume of soil (equivalent to the thickness of each monitored layer). In other
244 words, the value obtained by the probe placed at a depth of 0.05 m was considered representative of
245 the soil layer between 0 m and 0.10 m depth, whilst the soil water content value obtained by the
246 0.15 m depth probe was considered representative of the soil layer between 0.10 m and 0.225 m of
247 depth, and thus forth for the deeper probes. Thus, the volumes of water that infiltrated the soil and

the evolution of the water content profiles over time during the irrigation process (Fig. 2) were obtained for the three farms.

2.6 The measurements of irrigation parameters

Field measurements were performed to acquire the following data for each monitored irrigation event: i) the duration of the irrigation event, t_{ir} (T); ii) the irrigation inflow rate, F_r ($L^3 T^{-1}$); iii) the volume of water delivered during the irrigation event, V_d (L^3), and average volume of water delivered per unit area, ($L^3 L^{-2}$); and iv) the water head imposed on the field surface during the irrigation event, h_{surf} (L), which was measured by a water level staff gauge (marked at every millimetre) under steady flow conditions at the upstream position. We also recorded the occurrence of surface runoff, the time at which the surface runoff was eventually starting. The volume of surface runoff and deep percolation were not measured. They were calculated from the partition of the applied water volume determined from infiltration profiles as explained in the following section. Furthermore, the number of irrigation events initiated during the season by each farmer, the irrigation parameters and the infiltration advance profiles were used to partition the applied water volumes.

2.7 Partitioning of the applied water volume

The volume of storable water at field capacity V_{fc} (L^3) was calculated by multiplying the water content at field capacity by the volume of soil in the root layer. The soil water content at field capacity was calculated as the soil water content value given by the van Genuchten (1980) equation for the matric potential value of -3.3 m. Using the infiltration advance profiles and the scheme given in Figure 3, the volume of water applied to the field was partitioned as follows: i) the total volume of water stored in the soil V_{st} (L^3), which was calculated by subtracting the water volume lost through deep percolation from the total infiltrated volume and then adding the volume stored on the surface; ii) the volume stored at the surface V_s (L^3), which is the volume of water on the surface of the field after the completion of the water application; iii) the volume of water lost by surface runoff

273 V_r (L^3), which was calculated as the sum of the infiltrated water volume and the volume of water
274 stored on the land surface beyond the end of the field (when the irrigation ended); and iv) the
275 volume lost through deep percolation below the root layer V_{dp} (L^3). The volume of water stored on
276 the surface (V_s) was divided into two parts. The amount of the V_s that remained on the portion of the
277 field where deep percolation occurred was considered lost. The remaining volume was added to the
278 stored volume. The errors introduced by such assumptions are small because V_s never exceeded
279 10% of the stored volume (Table 4).

280 The volumes of water lost by surface runoff and deep percolation were not measured. They were
281 calculated from the infiltration profiles given by the infiltration advance model. Considering that the
282 model was validated on the infiltrated water depth at the locations of the TDR stations (as shown in
283 section 3.1) and the aim of the work was to employ simple measurement techniques, we choose not
284 to measure the volume of water lost by runoff and deep percolation. Such measurements were not
285 necessary for the validation of the model and their acquisition would have severely complicated the
286 field measurement campaigns.

287 All calculated water volumes were used to compute the application efficiency (E_a), the storage
288 efficiency (E_s), and the distribution efficiency (E_d) terms for the field-equivalent parameters. For
289 further comparison, the efficiency terms were also calculated for the three sets of parameters
290 determined by the infiltration BEST tests. Finally, the proposed model was used to simulate the
291 effects of changes in various irrigation parameters, namely, the flow rate (F_r), the irrigation event
292 duration (t_{ir}), the volume of water delivered (V_d) and the initial soil moisture θ_i .

293 *2.8 Irrigation efficiencies*

294 The application efficiency (E_a) quantifies the volume of water actually stored in the root layer in
295 relation to the volume of water delivered. The storage efficiency (E_s) quantifies the recovery of the
296 field water deficit. The distribution efficiency (E_d) quantifies the homogeneity of water storage
297 along the field. The combination of these three efficiency terms provides the global efficiency of the

298 irrigation process. Additionally, by employing the proposed method, the choice of the best irrigation
299 practice may be achieved.

300 The water application and storage efficiencies are given according to the relationships proposed by
301 Kruse et al. (1990):

$$302 \quad E_a = \frac{V_{st}}{V_d}, \quad (10)$$

$$303 \quad E_s = \frac{V_{st}}{V_{fc}}, \quad (11)$$

304 The distribution efficiency is determined using the relationship proposed by Burt et al. (1997):

$$305 \quad E_d = \frac{V_{lq}}{V_{fq}}, \quad (12)$$

306 where, V_{lq} is the volume of water stored in the last quarter of the field (L^3), whilst V_{fq} is the volume
307 stored in the first quarter of the field (L^3).

308 *2.9 Predictive simulations*

309 After the irrigation efficiencies of the monitored events were calculated, and the model was
310 employed to predict the irrigation efficiencies of simulated irrigation events. In particular, the
311 irrigation simulations were performed using seven different combinations of the irrigation
312 parameters (i.e., V_d , F_r and θ_i) to determine their influence on irrigation efficiency. The values of
313 the irrigation parameters are presented and discussed in section 3.4.

314 **3 Results and Discussion**

315 *3.1 Model validation*

316 The first step of the model validation was the confirmation of the short duration assumption. For the
317 measured irrigation times used in this study, the calculated values of x_k and τ_k , as proposed by
318 Knight (1980), corresponded to a short-duration behaviour. These parameter values are given in
319 Table 5. The dimensionless time and advancement variables never exceeded the maximum values
320 ($\tau_{max} = 1.4$ and $x_{max} = 0.4$) proposed by Knight (1980). According to Knight (1980), employing this

321 combination of values ensures that the behaviour of the Philip and Farrell analytical solution
 322 matches the actual advance-infiltration processes.

323 Using the proposed method, the field-equivalent saturated conductivity (K_{Seq}) values, obtained by
 324 fitting of Eqs. (1,2 and 5) as explained in section 2.1, were close to the three sets of values
 325 estimated by the BEST infiltration tests (Tables 6 and 7). The differences among the K_{Seq} values and
 326 the results of the corresponding BEST tests were almost always lower than 16% of the K_S values
 327 obtained from BEST tests. Only two differences exceeded that range. Both values were recorded at
 328 Farm 2, one in the year 2007 (36.7%) and the other in the year 2008 (-40.9%), as shown in Table 7.

329 The results of the BEST tests indicated low K_S variability across the fields of Farm 1 and Farm 3, as
 330 shown by the standard deviation of K_S values (Table 6) and by the three K_S values measured at each
 331 field, and among the three-year period (Table 7). The low variability of K_S was probably attributed
 332 to the tillage practices: each year, the soil structure was effectively destroyed by the rototilling
 333 practices performed prior to sowing. In any case, for further comparison, the root mean square error
 334 (RMSE) between the results of seven different pedotransfer functions applied for the estimation of
 335 K_S and the K_{Seq} values were evaluated. The RMSE between the results of the BEST tests and the
 336 K_{Seq} values were also evaluated. The K_S values are depicted in Figure 4 and the RMSE are listed in
 337 Table 8. Only one of the seven pedotransfer functions (Puckett et al., 1985) produced results that
 338 are in agreement with the estimated K_{Seq} values.

339 The infiltration depths of water were then compared with the infiltration profiles, which were
 340 calculated using the fitted K_{Seq} values (Table 6), the K_S values obtained by the BEST tests, and the
 341 irrigation parameters chosen by the farmers. The infiltration depths were obtained from the TDR
 342 soil water content measurements. Finally, the differences between the infiltration profiles and the
 343 infiltrated depth of water were assessed. The infiltration model outputs were always in good
 344 agreement with the measured infiltration depths (Fig. 5), as shown by the differences between
 345 simulated and measured infiltration depths reported in Table 9. The highest and the lowest
 346 differences recorded during the fifteen monitored events were 0.018 m and 0.002 m. The SRS

347 calculated to evaluate the performance of the proposed method on the monitored irrigation events
 348 was 0.22 at Farm 1, 0.07 at Farm 2 and 0.05 at Farm 3. Cook et al. (2013) found SRS values
 349 between 0.29 and 6.83 for the Philip and Farrel (1964) infiltration-advance solution for short-term
 350 duration. The low SRS obtained in our experiments is due to the direct measurement of the
 351 infiltration depth. Cook et al. (2013) employed infiltration depths estimated by Taylor (1981) using
 352 the mass balance method of Finkel and Nir (1960). The highest difference between the simulated
 353 and measured data observed during the first irrigation event performed by farm 1 in 2007 was 0.013
 354 m. This difference was recorded at a station located 30 m from the beginning of the field at 720 s
 355 and 913 s (t_{ir}) after the start of irrigation. The simulated infiltration depths were 0.178 m and 0.203
 356 m, respectively, and the measured depths were 0.191 m and 0.216 m, respectively. The minimum
 357 difference occurred during the same irrigation event, was recorded at 360 s after the start of
 358 irrigation, at a station located 32 m from the beginning of the field. The simulated infiltration depth
 359 was 0.116 m and the measured depth was 0.114.

360 *3.2 Irrigation efficiencies vs. hydraulic parameters*

361 As expected from Eqs. 1, 2 and 5, the analysis of the influence of the initial water content on the
 362 volume of water that might infiltrate the soil demonstrates the relationship between θ_i and the
 363 irrigation efficiency. The analysis of irrigation events performed at the constant values of K_S and F_l ,
 364 and similar values of F_r , indicate that a high θ_i results in low E_a values because of the low
 365 infiltration rate and, consequently, high surface runoff. Moreover, high θ_i values indicate a low soil
 366 retention capacity, which results in deep percolation losses even during low infiltration events.

367 The K_{Seq} values and the three K_S values estimated by the BEST infiltration tests were used to
 368 calculate four sets of efficiency values. The analysis of the application and storage efficiency values
 369 indicates that K_S has only a minor influence on the results (Figs. 6a and 6b) because the variability
 370 in K_S was very low. The low variability in K_S values could only transform deep percolation losses
 371 into runoff losses when there was little change in the volume of water stored in the root layer. Thus,

the distribution efficiency is more highly influenced by K_s than the other two efficiencies (Fig. 6c) because it depends on the shape of the infiltration profile and can be modified by small variations in K_s . The variation among the E_a values of the irrigation events was negligible (below 0.05) in almost all cases. As indicated in Figure 6a, we observed the highest variation of E_a in the first irrigation performed on farm 3 in 2006 (0.06). The variation among the E_s values was also negligible in almost all cases; the highest value was also observed for the first irrigation performed on farm 3 in 2006 (0.07), as shown in Figure 6b. The variation among E_d values was negligible for six of the fifteen irrigation events monitored; the highest E_d value was again observed for the first irrigation performed on farm 3 in 2006, as shown in Figure 6c, but this value was much higher (0.27) than the values found for E_a and E_s .

3.3 Irrigation efficiencies vs. irrigation parameters

The irrigation parameters varied considerably during the study period. In fact, the farmers were completely free to manage the irrigation events. Relying on their experience and on an empirical evaluation of the soil water content, many farmers tried to limit the effect of the initial water content by varying the volume of irrigation water and, in several cases, the flow rate (Table 10). Because of farm management needs, the farmers also changed the lengths of several plots during the three-year period.

The variations in the lengths of the plots, combined with a non-proportional variation in the flow rate and the temporal variability of the field-scale saturated hydraulic conductivity, resulted in variations in the time required for the water to reach the end of the field (t_{fl}). Additionally, this variation caused i) a modification of the time required to impose a uniform hydraulic head over the entire field surface and ii) a change in the volume of infiltrated water that, in some cases, was large enough to mask the effects of the initial water content. To limit the effects of the farmers' choices and to assess the real influence of t_{fl} and θ_i on irrigation efficiency, the analysis was conducted on pairs of irrigation events in which the other parameters were maintained nearly as constants.

397 As indicated in Eqs. (1) and (5), the analysis of irrigation events performed with constant values of
398 K_s and F_l and similar values of F_r indicate that the effect of t_{fl} on irrigation efficiency is inversely
399 proportional to θ_i . High θ_i values are associated with low t_{fl} values, which result in low E_a values
400 because of the high surface runoff. Low t_{fl} values are associated with the rapid imposition of a
401 constant head over the bay, which causes high values of E_s and E_d (Figs. 6b, 6c). Only a few
402 exceptions were found. In the examined pairs of irrigation events, the exceptions were explained by
403 the differences in t_{ir} and F_r employed by the farmers.

404 By employing higher flow rates, each of the farms achieved higher distribution efficiency values.
405 However, because of the surface runoff, the benefits of a higher E_d often did not compensate for the
406 decrease in the application efficiency values. The irrigation time (t_{ir}) cannot be decrease to approach
407 t_{fl} to avoid surface runoff because a low t_{ir} would cause a great difference in the time of infiltration
408 between upstream and downstream areas, which would strongly reduce the distribution efficiency
409 values. The best compromise was often achieved by modifying the flow rate. However, if the
410 irrigation district is provided with a network of gully channels, the volumes of water lost as surface
411 runoff should not be counted among the losses that affect the application efficiency (Clemmens et
412 al., 2008).

413 In most cases, the volumes of water stored during the monitored irrigation events balanced the
414 hydraulic deficit of the root layer. However, whilst the irrigations performed at farm 1 resulted in
415 water storage efficiencies that were significantly lower than one, all of the irrigations performed at
416 farm 2 and 3 resulted in higher E_s values, but with the disadvantage of high deep-percolation losses.

417 *3.4 Scenario analysis and considerations for predictive settings*

418 The infiltration profile across the entire field, which was simulated using the actual parameters of
419 the first irrigation event that was performed at farm 1 in 2007 (Fig. 7a), was compared with the
420 infiltration profiles produced by seven irrigation simulations. In the first three cases (Figs. 7b to 7d),
421 the duration of the irrigation event and the flow rates were altered. The infiltration profiles

described by cases 4-7 (Fig. 7e to 7h) were produced with differing flow rates and initial water contents. The values of the input parameters employed in the simulations are summarized in Table 11 in addition to the simulation results.

In the first case (Fig. 7b), the flow rate was reduced to a value of $0.04 \text{ (m}^3 \text{ s}^{-1}\text{)}$, whilst the duration of the irrigation event was increased by approximately one-third (1200 s) (Table 11). In this case, an E_a value of 0.95 was achieved because the water flowed only slightly past the end of the field and slightly deeper than the bottom of the soil root layer; hence, there were only small amounts of surface runoff and percolation losses. Although the watering volume of this first case was greater than that of the real monitored case, the majority of the water was stored equally and the E_s was slightly improved because of this level of storage. In contrast, there was a reduction in E_d that caused a reduction in the overall irrigation efficiency.

In the second case (Fig. 7c), the flow rate was equal to the previous case (Table 11), but the duration of the irrigation event was increased by one-third (1600 s). The results indicate an improvement in the E_s and E_d and a decrease in the E_a value. The watering volume considered in this case was higher than the two previous cases, which suggests that the necessary watering volume was surely underestimated for the monitored case.

In the third case (Fig. 7d), the flow rate was the same as in the real irrigation event, whilst the event duration was the same as in the second case, thus applying a watering volume that was almost twice as large as the volume of the real irrigation event. In this case, both the E_s and E_d increased to a value of 1, but the E_a value (0.64) was the lowest among all of the cases considered (Table 11).

In the fourth case (Fig. 7e), the flow rate was increased to a value of $0.06 \text{ (m}^3 \text{ s}^{-1}\text{)}$ but the irrigation duration was maintained at the actual value used by the farmer (Table 11). Compared to the real irrigation event, the results indicate an increase in the E_s (+0.04) and E_d (+0.10) and a decrease in the E_a (-0.11). The E_a value was comparable to the value obtained in the second case, but the E_s and E_d values were lower.

447 In the fifth case (Fig. 7f), the flow rate was increased to a value of $0.07 \text{ (m}^3 \text{ s}^{-1}\text{)}$, whilst the irrigation
 448 event duration was maintained at the actual irrigation duration. Compared to the previous case, the
 449 E_s and E_d increased slightly ($+0.02$ and $+0.07$, respectively). In this case, the E_a value was slightly
 450 lower than in the second case, whilst the storage efficiency value decreased by 0.12 .

451 In the sixth case (Fig. 7 g), the flow rate and the irrigation event duration values were the same as
 452 the values from the real irrigation event (Table 11), but the initial soil water content was set to a
 453 value of $0.05 \text{ (m}^3 \text{ m}^{-3}\text{)}$, which is lower than the measured value. Compared to the real event, the
 454 results suggest an increase in the E_a ($+0.05$) because of the higher infiltration rate caused by the
 455 high value of the matric potential, which is inversely proportional to the soil water content.

456 When compared to the real irrigation event, the results of the first six cases also indicate a reduction
 457 in the E_s because the water deficit was higher in these simulations. Additionally, the results
 458 demonstrate a reduction in the E_d because of the difference in the depth of water infiltration at the
 459 beginning and at the end of the field during the time required to establish a uniform hydraulic head
 460 over the field. The simulation results suggest that, when the irrigation is performed at a θ_i that is
 461 lower than in the actual irrigation event considered, the flow rate should be increased.

462 Finally, in the seventh simulation (Fig. 7 h), the initial water content was assumed to be higher than
 463 the real value and was set to a value of $0.15 \text{ (m}^3 \text{ m}^{-3}\text{)}$. However, the other parameters were the same
 464 as in the real irrigation event (Table 11). As expected, the results were the opposite of the previous
 465 case. Compared to the real event, the E_a decreased (-0.06) and both the E_s and E_d increased to $+0.12$
 466 and $+0.10$, respectively.

467 According to the simulation results, the best E_a value was obtained for the sixth case, but the
 468 corresponding E_s and E_d values were the lowest. This result suggests that this choice would
 469 represent a misuse of water. In contrast, the best E_s and E_d values were registered in the third case,
 470 but the E_a value was the lowest. The real irrigation event considered represents a compromise
 471 between saving water and the best use of water for crop production. The second case is also a good
 472 compromise because a slightly greater volume of water is employed to obtain a large increase in E_s

473 and E_d . A higher flow rate was not always the best solution. A comparison between the results of
474 the fourth and fifth cases indicates that a high flow rate could be employed to increase the E_s and E_d
475 values. However, this solution can only be applied in cases where the irrigation district is provided
476 with a network of gully channels to avoid surface runoff losses and maintain high values of E_d .
477 For the monitored irrigation events, the flow rate employed by the farmer was suitable for the field
478 conditions, whereas the watering volume was insufficient, as shown in the third simulation (Fig.
479 7d). Similar to the previous simulations, the sixth and seventh simulations (Fig. 7 g and 7 h)
480 demonstrated the influence of the initial field conditions. These results suggest that farmers should
481 apply larger watering volumes, but less frequently, to obtain higher irrigation efficiencies.
482 Moreover, to avoid low E_s and E_d values, irrigation should not be performed when the soil water
483 content is too low.

484 **5 Conclusions**

485 In this study, a method based on the Philip and Farrel (1964) advance-infiltration model was
486 proposed for i) calculating the border irrigation efficiency from four simple field measurements
487 (inflow rates, irrigation durations, and soil water content values monitored at only one point of the
488 field at the beginning and at the end of the irrigation processes) and ii) for testing the sensitivity of
489 irrigation efficiency to surface irrigation operational parameters.

490 The irrigation efficiency of 15 real irrigation events performed on three different farms during the
491 growing seasons in 2006, 2007 and 2008 were analysed. Finally, a scenario analysis based on data
492 collected during one of the surveyed events was also performed by altering the irrigation parameters
493 that affect irrigation efficiency (namely, irrigation duration, flow rate, and initial soil water content).
494 The proposed method proved to be capable of describing real irrigation practices. Moreover, the
495 method was capable of evaluating the changes in irrigation efficiency as a consequence of
496 variations in the operational irrigation parameters.

497 The results demonstrate that the equivalent saturated hydraulic conductivities estimated using the
498 proposed method is always in good agreement with the K_s values estimated using the infiltration
499 tests performed at three different positions in each field. Additionally, the irrigation efficiencies
500 calculated using both the proposed approach and using the parameters estimated by infiltration
501 measurements were in good agreement.

502 The efficiencies analysis (of the water application, storage, and distribution efficiencies) highlighted
503 the marked variability in the values among the monitored farms and within each farm. This level of
504 variability was associated with the variations in the watering volumes and flow rates. The influence
505 of the initial soil water content on the storage efficiency was clear, but some exceptions were
506 observed when irrigation durations was sufficiently long to mask the effects of the initial soil water
507 content.

508 The analysis of both the simulated scenarios and fifteen monitored irrigation events demonstrated
509 the need to irrigate these fields using lower flow rates and higher irrigation durations than those
510 currently used by the farmers. The scenario analysis also revealed that the irrigation efficiencies are
511 highly dependent on the initial soil water content.

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650 **FIGURE CAPTIONS**

651 **Fig. 1** Example of volumetric soil water content data collected by a TDR station with probes
652 inserted below a row. The represented survey was performed during the first irrigation event at farm
653 2 (in 2008). The vertical line indicates the end of the irrigation event. The 0.65 m depth data are
654 missing because a layer of stones prevented the insertion of a TDR probe.

655 **Fig. 2** Example of soil water content profiles measured with the TDR technique every 5 minutes
656 during the first irrigation event performed at farm 1 in 2006. The lines represent the water content
657 profiles computed every 5 minutes from the beginning of the irrigation event, t_0 , until the end of the
658 irrigation event. The vertical axis, z , indicates the soil depth.

659 **Fig. 3** Diagram of an infiltration profile in which the whole water volume is subdivided into five
660 portions. The horizontal black line represents the field surface, and the vertical line represents the
661 end of the field. The data represent the real irrigation event performed on July 2008 at farm 3.

662 **Fig. 4** Comparison of the saturated hydraulic conductivity values estimated by seven different well-
663 known pedotransfer functions and the field-equivalent values estimated by the proposed method
664 (K_{s_eq}). The tested pedotransfer functions are indicated as follows: Cosby et al. (1984) = (K_{s_C});
665 Saxton et al. (1986) = (K_{s_S}); Brakensiek et al. (1984) = (K_{s_B}); Ferrer-Julià et al. (2004) =
666 (K_{s_F}); Campbell and Shiozawa (1994) = (K_{s_CS}); Puckett et al. (1985) = (K_{s_P}); and Dane and
667 Puckett (1994) = (K_{s_DP}).

668 **Fig. 5** Soil water infiltration profiles observed during the first irrigation event performed at farm 1
669 in 2007. The circles represent the depths of water infiltration that were measured using TDR probes.
670 The curved lines represent the water content profiles calculated every 5 minutes from the beginning
671 of the irrigation event (t_0) until the end of the irrigation event (t_{ir}). The imposed hydraulic head

672 (dash-dotted line) corresponds to the volume of water stored on the field surface divided by the total
673 surface. The vertical axis, z , indicates the soil depth.

674 **Fig. 6** Application efficiencies (E_a) (a), storage efficiencies (E_s) (b) and distribution efficiencies (E_d)
675 (c) calculated from the infiltration profiles obtained by using the field-equivalent saturated
676 hydraulic conductivity values and the three sets of saturated hydraulic conductivity values estimated
677 by the BEST infiltration tests. The irrigation events (x axis) are identified as farm: irrigation event:
678 year.

679 **Fig. 7** Infiltration-profile scenario analysis based on the data collected during the first irrigation
680 event performed at farm 1 in 2007. The real case is depicted in box (a) whilst the simulated cases,
681 obtained by modifying the soil and irrigation parameters, are shown in boxes (b to h). The values of
682 the parameters for the scenarios are listed in each single box: initial soil water content (θ_i), watering
683 volume (V_d), flow rate (F_r) and irrigation duration (t_{ir}).

684 (a) The circles represent the depths of water infiltration measured using the TDR technique. The
685 dotted vertical line and dashed vertical line indicate the locations of the two TDR probe profiles,
686 which were located at 30 m and 32 m from the beginning of the field, respectively.

687 **TABLE CAPTIONS**

688 **Tab. 1** Saturated and field-capacity water content values of the examined soils.

689 **Tab. 2** Soil texture and the percentages of stones in the three different farm soils monitored.

690 **Tab. 3** Plot size variability during the three-year monitoring period.

691 **Tab. 4** Relationship between the water volume stored on the surface (V_s) and the water volume
692 stored in the root layer (V_{rt}) for the fifteen monitored irrigation events.

693 **Tab. 5** Calculated values of the dimensionless parameters t_k (-), C_k (-), and x_k (-) for the Philip and
694 Farrell analytical solution.

695 **Tab. 6** Field-equivalent saturated hydraulic conductivity values (cm h^{-1}) calculated for each farm
696 and each year during the period from 2006-2008.

697 **Tab. 7** Saturated hydraulic conductivity values (cm h^{-1}) estimated by means of the three BEST tests
698 for each farm and each year during the period from 2006-2008. Differences between estimated
699 saturated hydraulic conductivity and corresponding K_{Seq} values are given in brackets as percentage
700 of saturated hydraulic conductivity.

701 **Tab. 8** RMSE calculated between the K_{Seq} values and the K_S values estimated by pedotransfer
702 functions and BEST tests.

703 **Tab. 9** Differences between simulated and measured infiltration depths. The differences were
704 calculated at 180 s (t_1), 360 s (t_2), 540 s (t_3), 720 s (t_4) from the start of the irrigation events and at
705 the end of them (t_{ir}) at the locations of the TDR profiles (30 m - x_1 - and 32 m - x_2 - from the
706 beginning of the field).

707 **Tab. 10** Volumetric soil water content at the beginning of the irrigation event (θ_i), irrigation water
708 volume (V_d), flow rate (F_r), irrigation event duration (t_{ir}), time required for the water front to reach
709 the end of the field (t_f), field length (F_l), and values of the water application efficiency (E_a), water
710 storage efficiency (E_s), and water distribution efficiency (E_d) for each irrigation event monitored
711 during the period from 2006-2008.

712 **Tab. 11** Volumetric soil water content at the beginning of each irrigation event (θ_i), irrigation water
713 volume (V_d), flow rate (F_r), irrigation event duration (t_{ir}), field length (F_l), and values of the water
714 application efficiency (E_a), water storage efficiency (E_s), and water distribution efficiency (E_d) for
715 the first irrigation event performed at farm 1 in 2007 and the seven simulated scenarios.

716 **TABLES**

717

| | Saturated soil water content (m ³ m ⁻³) | | | | Field capacity soil water content (m ³ m ⁻³) | | | |
|---------------|--|-------|-------|---------|---|-------|-------|---------|
| | 2006 | 2007 | 2008 | Average | 2006 | 2007 | 2008 | Average |
| Farm 1 | 0.405 | 0.398 | 0.424 | 0.409 | 0.347 | 0.341 | 0.363 | 0.350 |
| Farm 2 | 0.454 | 0.419 | 0.440 | 0.438 | 0.391 | 0.361 | 0.379 | 0.377 |
| Farm 3 | 0.426 | 0.414 | 0.427 | 0.422 | 0.381 | 0.371 | 0.382 | 0.378 |

718 **Table 1**

719

| 720 | | | | | |
|----------|----------|----------|----------|------------|------------|
| Farm | Sand (%) | Silt (%) | Clay (%) | Stones (%) | Texture |
| 1 | 20.4 | 71.1 | 8.5 | 20 | Silty Loam |
| 2 | 42.1 | 48.8 | 9.1 | 30 | Loam |
| 3 | 46.8 | 42.2 | 11 | 25 | Loam |

724 **Table 2**

725

| | 2006 | | 2007 | | 2008 | |
|----------|------------|-----------|------------|-----------|------------|-----------|
| Farm | Length (m) | Width (m) | Length (m) | Width (m) | Length (m) | Width (m) |
| 1 | 130 | 35 | 88 | 35 | 88 | 35 |
| 2 | 134 | 120 | 134 | 120 | 229 | 11 |
| 3 | 600 | 96 | 600 | 96 | 600 | 96 |

726 **Table 3**

727

| Irrigation event - year | | V_s/V_{rt} (m ³ m ⁻³) |
|-------------------------|----------|--|
| Farm 1 | 1 - 2006 | 0.10 |
| | 4 - 2006 | 0.04 |
| | 1 - 2007 | 0.06 |
| | 2 - 2007 | 0.09 |
| | 1 - 2008 | 0.09 |
| Farm 2 | 2 - 2006 | 0.10 |
| | 3 - 2006 | 0.10 |
| | 1 - 2007 | 0.10 |
| | 1 - 2008 | 0.03 |
| Farm 3 | 2 - 2006 | 0.04 |
| | 4 - 2006 | 0.05 |
| | 1 - 2007 | 0.05 |
| | 2 - 2007 | 0.10 |
| | 1 - 2008 | 0.08 |
| | 4 - 2008 | 0.10 |

Table 4

| | Farm 1 | | | | | Farm 2 | | | | | Farm 3 | | | | | 730 |
|----------|--------|------|------|------|------|--------|------|------|------|------|--------|------|------|------|-----|-----|
| | 2006 | | 2007 | | 2008 | 2006 | | 2007 | 2008 | 2006 | | 2007 | | 2008 | 731 | |
| | 1 | 4 | 1 | 2 | 1 | 2 | 3 | 1 | 1 | 2 | 4 | 1 | 2 | 1 | 732 | |
| τ_k | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 733 | |
| C_k | 0.21 | 0.11 | 0.07 | 0.07 | 0.19 | 0.1 | 0.15 | 0.14 | 0.13 | 0.11 | 0.13 | 0.12 | 0.16 | 0.15 | 734 | |
| x_k | 0.05 | 0.10 | 0.10 | 0.09 | 0.07 | 0.19 | 0.10 | 0.13 | 0.12 | 0.23 | 0.22 | 0.26 | 0.18 | 0.23 | 735 | |
| | | | | | | | | | | | | | | | 736 | |
| | | | | | | | | | | | | | | | 737 | |

Table 5

| | 2006 | 2007 | 2008 | Average | Standard deviation |
|--------|------|------|------|---------|--------------------|
| Farm 1 | 2.47 | 2.38 | 2.51 | 2.45 | 0.12 |
| Farm 2 | 4.64 | 5.02 | 1.76 | 3.81 | 1.17 |
| Farm 3 | 2.28 | 2.52 | 2.85 | 2.55 | 0.30 |

Table 6

742

| | BEST test 1 | | | BEST test 2 | | | BEST test 3 | | |
|--------|-------------|---------|---------|-------------|---------|---------|-------------|----------|---------|
| | 2006 | 2007 | 2008 | 2006 | 2007 | 2008 | 2006 | 2007 | 2008 |
| Farm 1 | 2.34 | 2.31 | 2.25 | 2.41 | 2.44 | 2.48 | 2.63 | 2.52 | 2.57 |
| | (5.3%) | (2.9%) | (10.4%) | (2.4%) | (-2.5%) | (1.2%) | (-6.5%) | (-7.1%) | (-2.4%) |
| Farm 2 | 3.96 | 3.18 | 1.61 | 4.35 | 4.28 | 1.87 | 4.66 | 4.91 | 2.48 |
| | (14.7%) | (36.7%) | (8.5%) | (6.3%) | (14.7%) | (-6.3%) | (-0.4%) | (-40.9%) | (2.2%) |
| Farm 3 | 1.93 | 2.36 | 2.51 | 2.16 | 2.48 | 2.73 | 2.54 | 2.51 | 3.07 |
| | (15.7%) | (7.8%) | (12.2%) | (5.7%) | (3.1%) | (4.5%) | (-10.9%) | (2.0%) | (-7.3%) |

743

Table 7

744

| | Ks_C | Ks_S | Ks_B | Ks_F | Ks_CS | Ks_P | Ks_DP | Ks_BEST #1 | Ks_BEST #2 | Ks_BEST #3 |
|------|------|------|------|------|-------|------|-------|------------|------------|------------|
| RMSE | 1.54 | 2.73 | 3.06 | 2.49 | 3.00 | 0.62 | 6.10 | 0.69 | 0.28 | 0.28 |

745

Table 8

746

| | | t_1 | t_2 | t_3 | t_4 | t_{ir} |
|------------------------|----------|--------|--------|--------|--------|----------|
| Farm 1 x_1 | 1 - 2006 | 0.012 | 0.009 | 0.005 | -0.005 | -0.012 |
| | 4 - 2006 | 0.006 | 0.007 | 0.006 | 0.003 | -0.002 |
| | 1 - 2007 | 0.003 | 0.005 | -0.009 | -0.013 | -0.013 |
| | 2 - 2007 | 0.006 | -0.003 | 0.004 | -0.004 | -0.005 |
| | 1 - 2008 | 0.007 | 0.005 | 0.004 | -0.007 | -0.006 |
| Farm 1 x_2 | 1 - 2006 | 0.008 | 0.006 | 0.007 | -0.003 | -0.093 |
| | 4 - 2006 | 0.003 | 0.008 | 0.007 | 0.004 | -0.007 |
| | 1 - 2007 | 0.006 | 0.002 | 0.002 | -0.005 | -0.004 |
| | 2 - 2007 | 0.007 | 0.004 | 0.005 | -0.004 | 0.003 |
| | 1 - 2008 | 0.011 | 0.01 | 0.012 | 0.009 | 0.004 |
| Farm 2 x_1 | 2 - 2006 | 0.007 | 0.004 | -0.005 | 0.006 | 0.01 |
| | 3 - 2006 | 0.006 | 0.006 | 0.007 | -0.004 | -0.018 |
| | 1 - 2007 | 0.011 | 0.018 | 0.004 | -0.006 | -0.004 |
| | 1 - 2008 | 0.01 | 0.007 | 0.005 | -0.008 | -0.005 |
| Farm 2 x_2 | 2 - 2006 | 0.006 | -0.003 | -0.008 | -0.009 | -0.012 |
| | 3 - 2006 | 0.004 | 0.004 | 0.002 | -0.003 | -0.007 |
| | 1 - 2007 | 0.018 | 0.011 | 0.006 | -0.003 | -0.008 |
| | 1 - 2008 | 0.007 | 0.013 | 0.01 | 0.005 | 0.005 |
| Farm 3 x_1 | 1 - 2006 | 0.003 | 0.003 | 0.005 | -0.006 | -0.008 |
| | 4 - 2006 | 0.009 | 0.008 | 0.01 | -0.004 | -0.005 |
| | 1 - 2007 | 0.004 | 0.007 | 0.011 | 0.008 | -0.006 |
| | 2 - 2007 | 0.011 | 0.012 | 0.015 | 0.003 | -0.01 |
| | 1 - 2008 | -0.017 | -0.018 | -0.005 | -0.003 | 0.012 |
| | 4 - 2008 | -0.008 | -0.007 | -0.005 | -0.011 | 0.007 |
| Farm 3 x_2 | 1 - 2006 | 0.011 | 0.009 | 0.006 | 0.004 | -0.009 |
| | 4 - 2006 | 0.007 | 0.012 | 0.008 | -0.005 | -0.004 |
| | 1 - 2007 | -0.006 | 0.004 | 0.012 | 0.009 | -0.009 |
| | 2 - 2007 | 0.012 | 0.011 | 0.009 | 0.004 | -0.006 |
| | 1 - 2008 | -0.01 | -0.01 | -0.006 | -0.003 | 0.011 |
| | 4 - 2008 | -0.007 | -0.006 | -0.003 | -0.008 | 0.009 |

Table 9

| | Monitored irrigation event - year | θ_i (m ³ m ⁻³) | V_d (m ³ ha ⁻¹) | F_r (m ³ s ⁻¹) | t_{ir} (s) | t_{fl} (s) | F_l (m) | E_a (-) | E_s (-) | E_d (-) |
|--------|---|---|---|--|-----------------|-----------------|--------------|--------------|--------------|--------------|
| Farm 1 | 1 - 2006 | 0.08 | 838 | 0.054 | 1513 | 1505 | 130 | 1.00 | 0.67 | 0.47 |
| | 4 - 2006 | 0.12 | 741 | 0.048 | 1505 | 1505 | 130 | 1.00 | 0.63 | 0.46 |
| | 1 - 2007 | 0.12 | 706 | 0.051 | 913 | 594 | 88 | 0.92 | 0.81 | 0.70 |
| | 2 - 2007 | 0.08 | 706 | 0.051 | 913 | 675 | 88 | 0.95 | 0.59 | 0.64 |
| | 1 - 2008 | 0.14 | 1482 | 0.060 | 1630 | 467 | 88 | 0.67 | 0.87 | 0.89 |
| Farm 2 | 2 - 2006 | 0.05 | 1772 | 0.125 | 1797 | 1034 | 130 | 0.72 | 0.99 | 0.97 |
| | 3 - 2006 | 0.13 | 1183 | 0.125 | 1200 | 843 | 130 | 0.81 | 0.96 | 0.86 |
| | 1 - 2007 | 0.12 | 1119 | 0.125 | 1135 | 898 | 130 | 0.72 | 0.98 | 0.92 |
| | 1 - 2008 | 0.13 | 1817 | 0.160 | 2925 | 784 | 229 | 0.53 | 1.00 | 1.00 |
| Farm 3 | 2 - 2006 | 0.12 | 1352 | 0.123 | 3957 | 3825 | 600 | 0.79 | 0.93 | 0.72 |
| | 4 - 2006 | 0.16 | 1409 | 0.128 | 3963 | 3144 | 600 | 0.69 | 0.98 | 0.93 |
| | 1 - 2007 | 0.08 | 1829 | 0.138 | 4771 | 3727 | 600 | 0.69 | 0.98 | 0.94 |
| | 2 - 2007 | 0.13 | 1577 | 0.159 | 3571 | 2326 | 600 | 0.65 | 1.00 | 0.99 |
| | 1 - 2008 | 0.07 | 2249 | 0.156 | 5190 | 3543 | 600 | 0.59 | 1.00 | 1.00 |
| | 4 - 2008 | 0.18 | 1791 | 0.161 | 4005 | 2250 | 600 | 0.60 | 1.00 | 1.00 |

Table 10

| | Irrigation event - year | θ_i (m ³ m ⁻³) | V_d (m ³ ha ⁻¹) | F_r (m ³ s ⁻¹) | t (s) | F_l (m) | E_a (-) | E_s (-) | E_d (-) |
|--------|-------------------------|--|--|---|---------|-----------|-----------|-----------|-----------|
| Farm 1 | 2 - 2007 - real case | 0.12 | 706 | 0.051 | 913 | 88 | 0.92 | 0.81 | 0.70 |
| | 2 - 2007 - case 1 | 0.12 | 727 | 0.040 | 1200 | 88 | 0.95 | 0.87 | 0.64 |
| | 2 - 2007 - case 2 | 0.12 | 970 | 0.040 | 1600 | 88 | 0.79 | 0.97 | 0.89 |
| | 2 - 2007 - case 3 | 0.12 | 1236 | 0.051 | 1600 | 88 | 0.64 | 1.00 | 1.00 |
| | 2 - 2007 - case 4 | 0.12 | 830 | 0.060 | 913 | 88 | 0.80 | 0.84 | 0.86 |
| | 2 - 2007 - case 5 | 0.12 | 968 | 0.070 | 913 | 88 | 0.71 | 0.86 | 0.87 |
| | 2 - 2007 - case 6 | 0.05 | 706 | 0.051 | 913 | 88 | 0.97 | 0.70 | 0.61 |
| | 2 - 2007 - case 7 | 0.15 | 706 | 0.051 | 913 | 88 | 0.86 | 0.92 | 0.79 |

Table 11

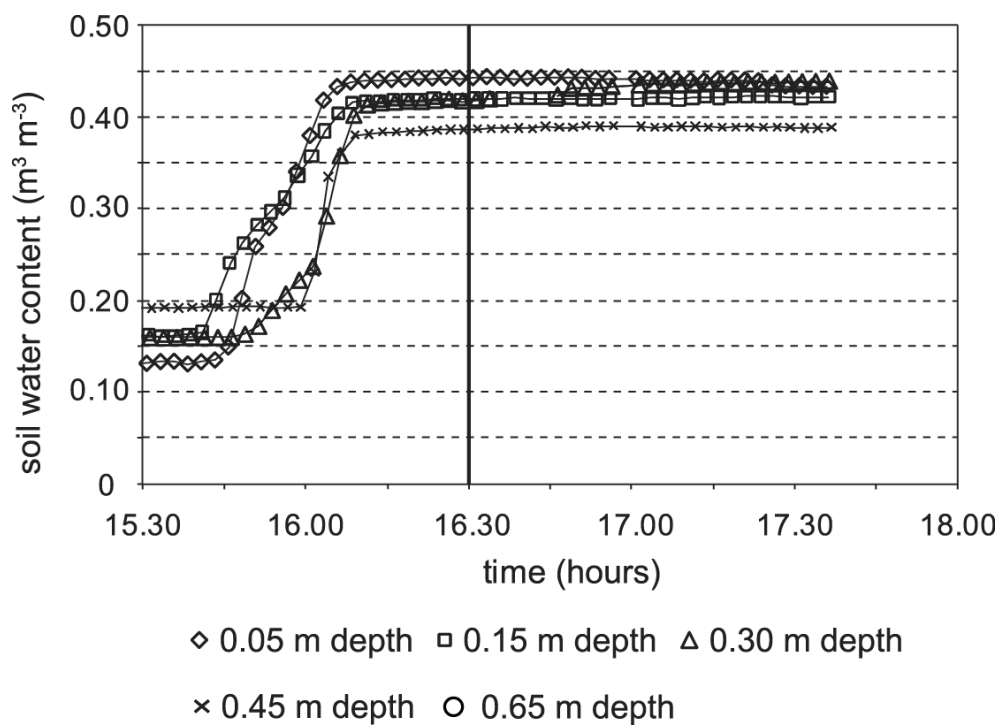


Figure 1

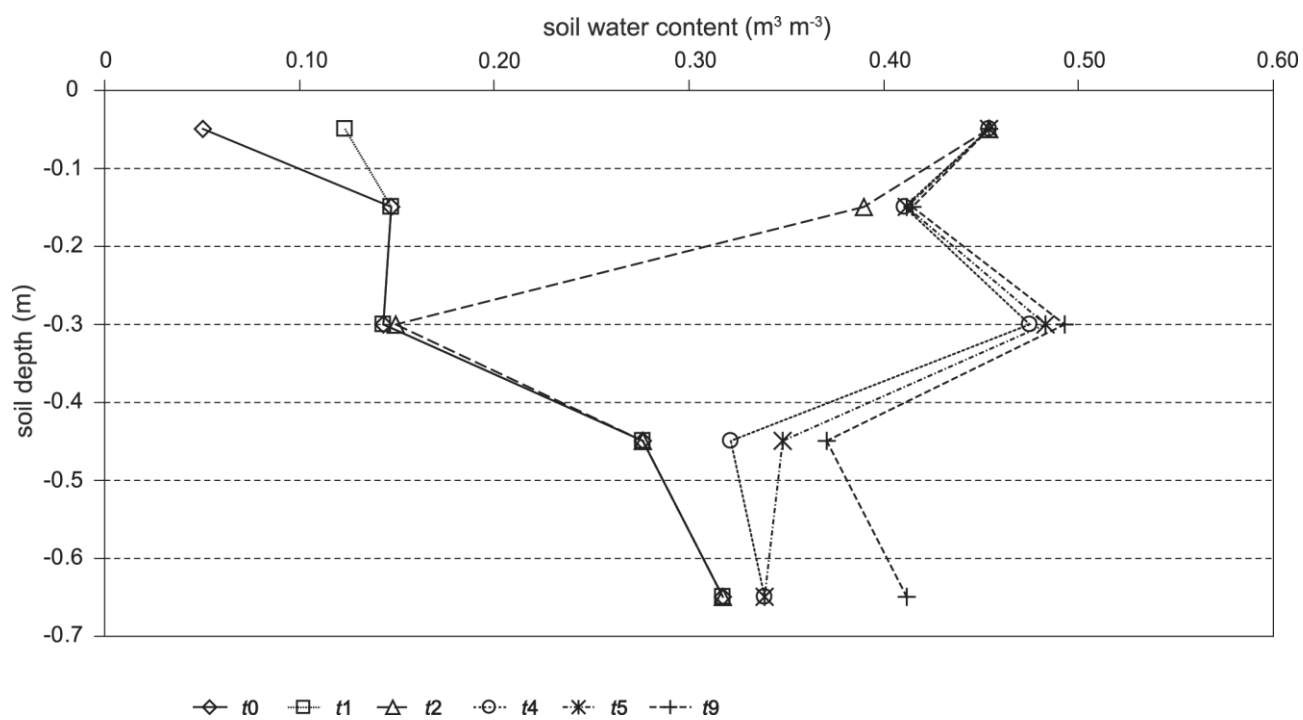


Figure 2

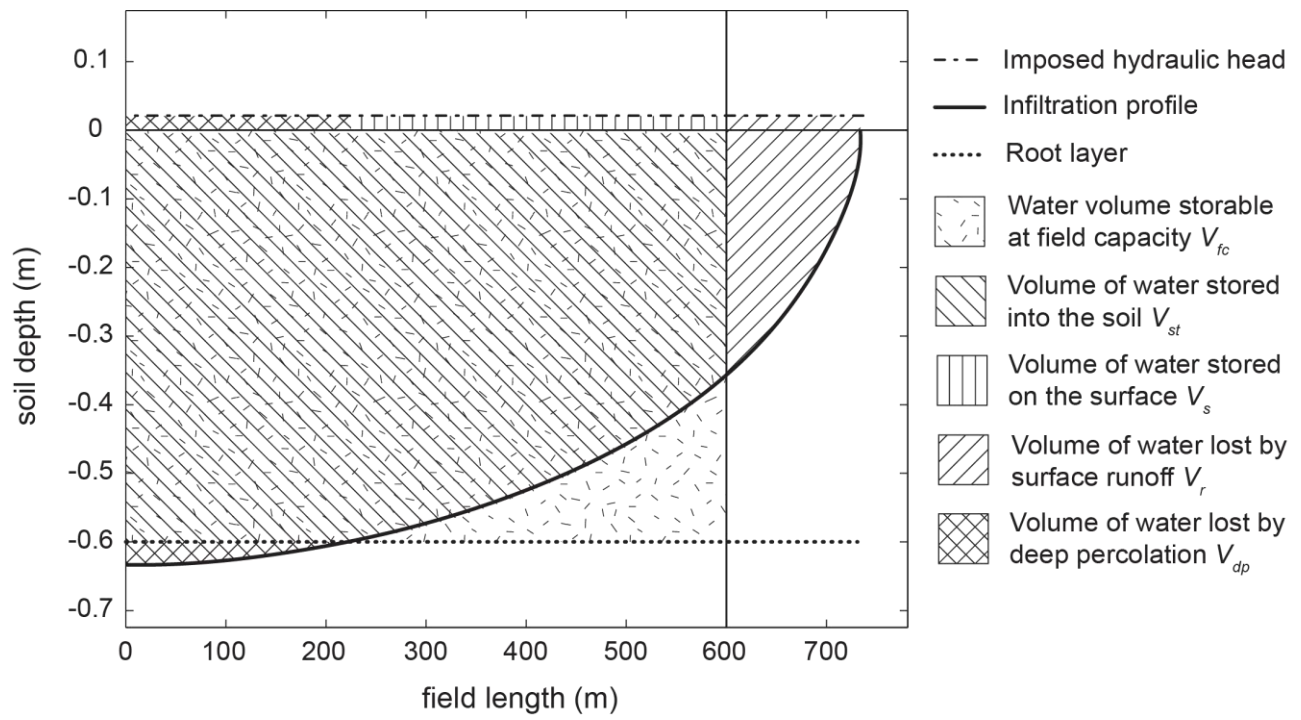


Figure 3

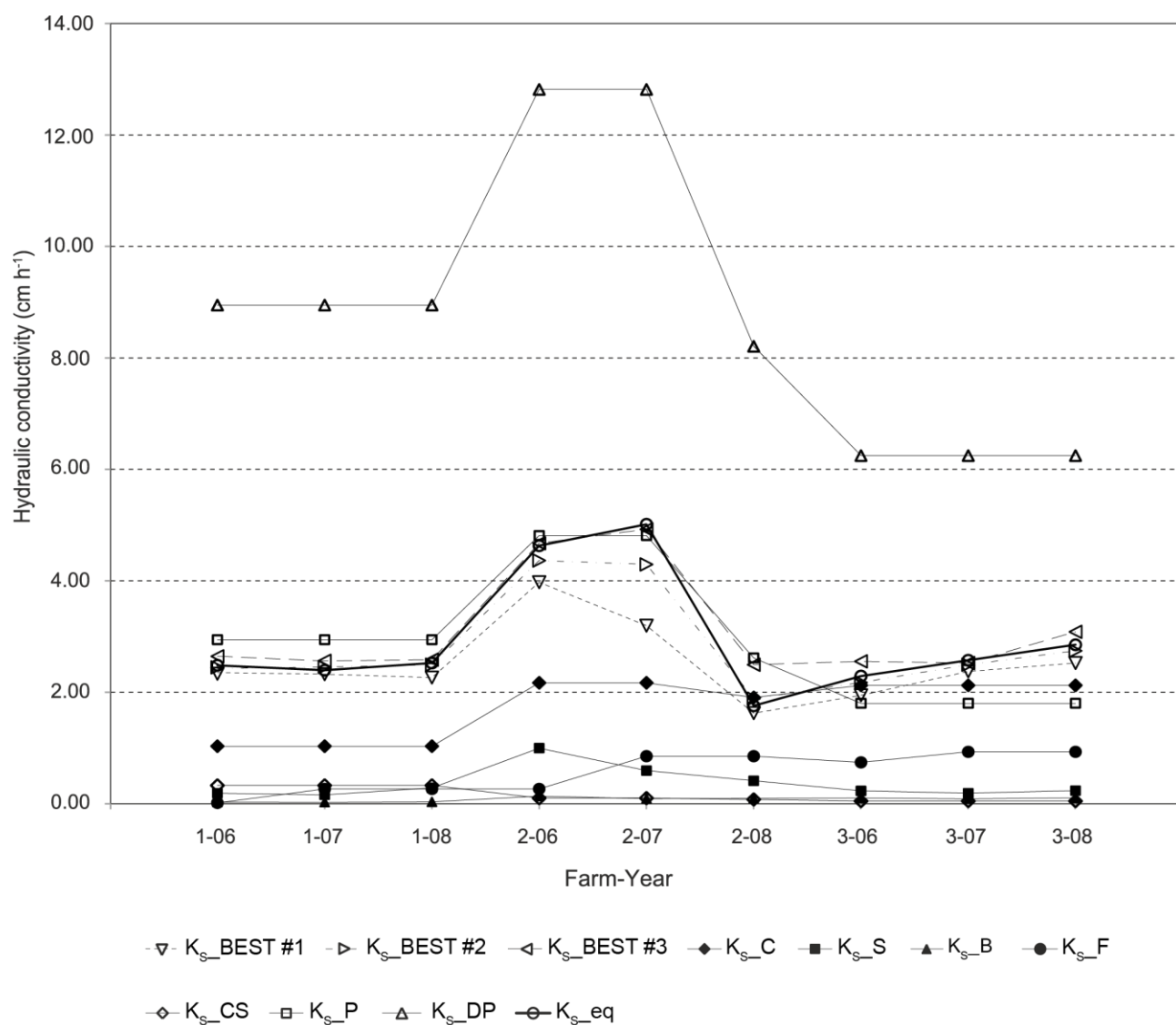


Figure 4

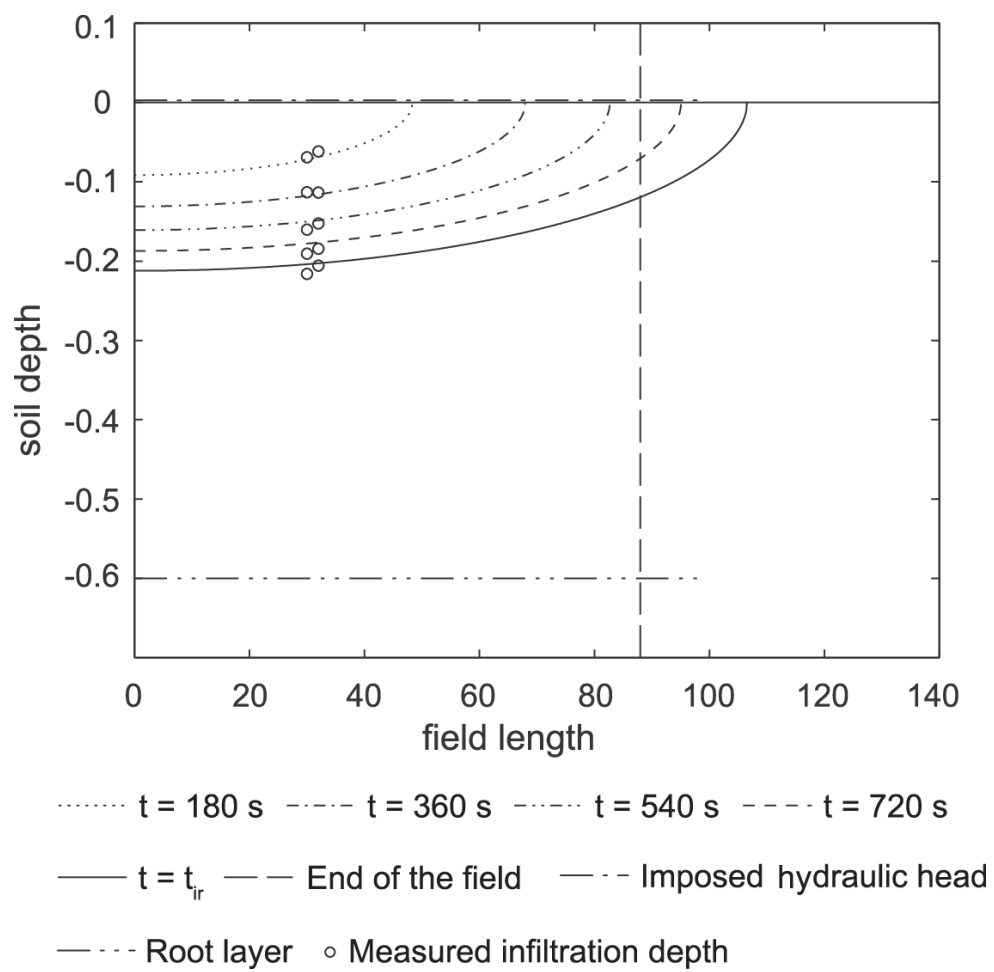


Figure 5

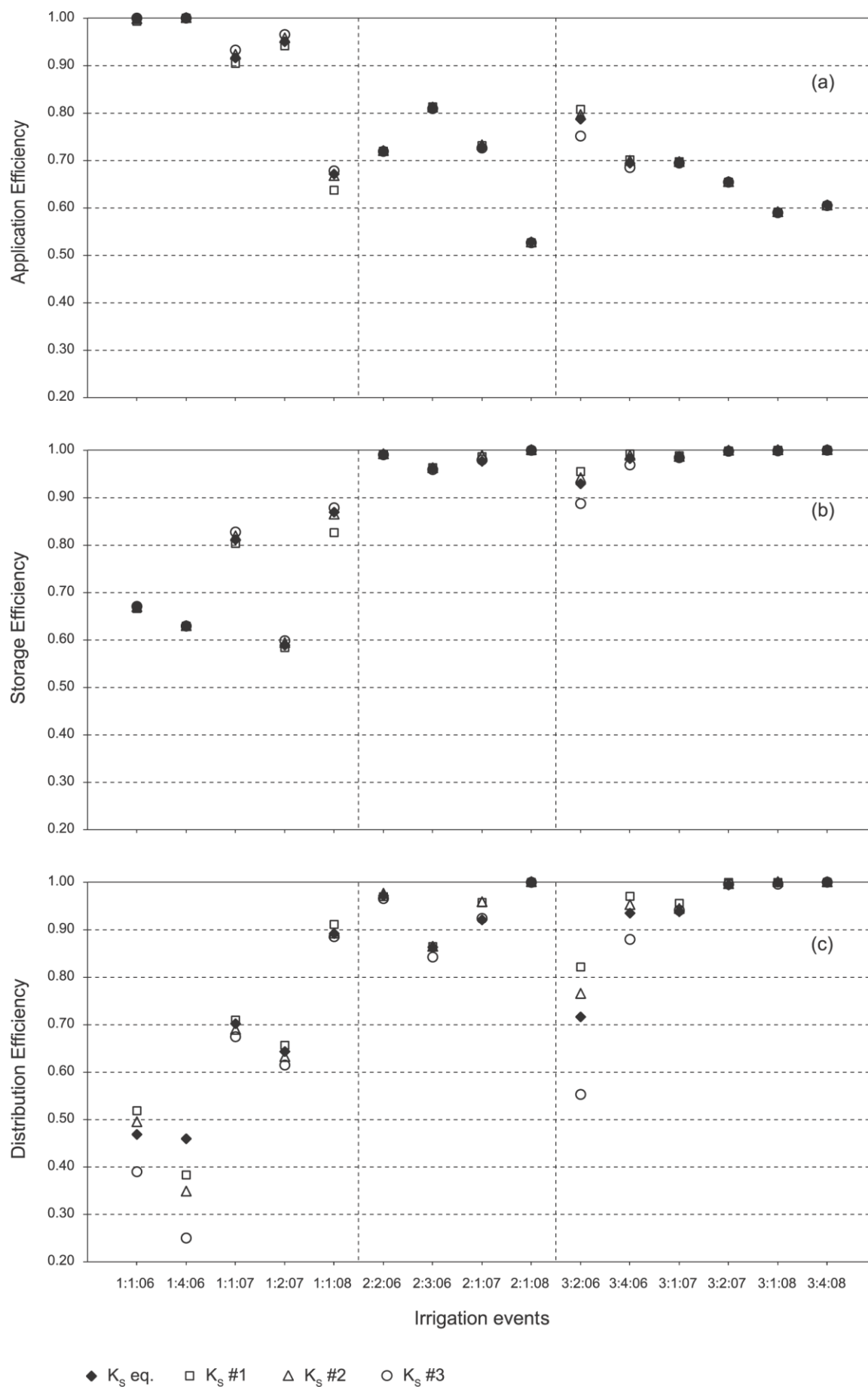


Figure 6

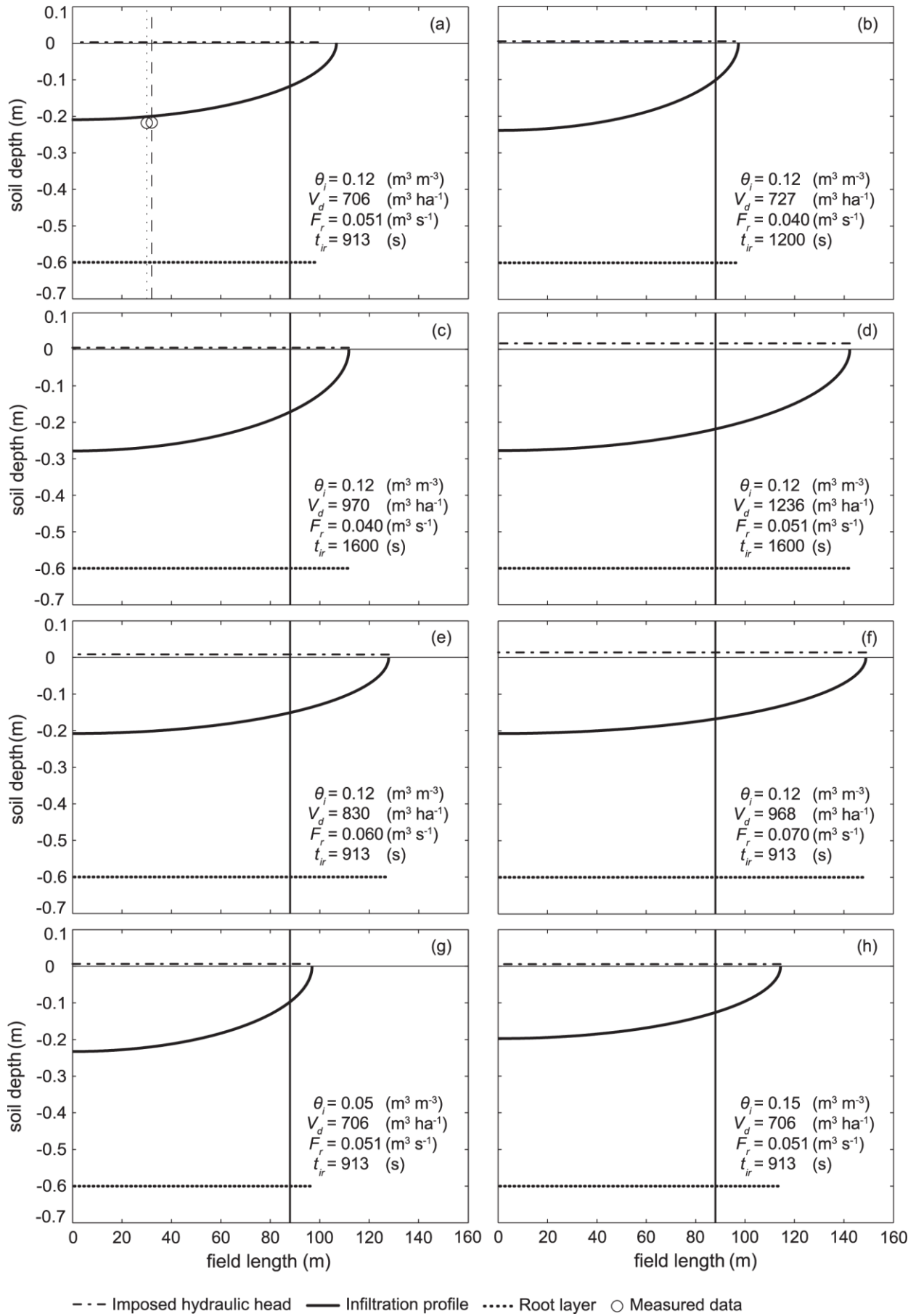


Figure 7